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Prescribed burning and productivity in southern pine forests: a review

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Abstract

Fire is an ancient tool but still widely used in the management of southern pine forests. Fire is a relatively inexpensive tool and has a number of beneficial uses such as removing logging debris, reducing wildfire risk, increasing the abundance of certain understory species, and maintaining or restoring certain ecological conditions. However, recent studies demonstrate that fire can play a significant role in regulating the productivity of certain ecosystems. Burning releases large quantities of carbon and essential nutrients to the atmosphere as gases and particulates. The adverse impact of these releases on air quality is widely recognized, but the potential impact of nutrient losses and changes in soil productivity have received less attention from southern pine managers. The effect of fire on nitrogen (N) pools is especially significant since N availability is one of the most common limiting factors in forest productivity. The amount of N lost during the burning of forest fuels is directly related to fuel consumption and ranges from 3 to 6 kg N Mg^{-1} of fuel consumed. The combined losses of N and other elements through harvesting and burning appear to exceed considerably the rate of replacement by natural processes, and may necessitate the regular application of fertilizer to maintain the nutrient capital of the site. Burning results in a short-term increase in soil available N and other nutrients immediately after burning, which stimulates the growth of understory vegetation; a desirable effect in some settings but also a source of competition for newly planted pine seedlings. A more thorough understanding of the biogeochemical effects of prescribed fire of varying frequencies and severities is needed to make optimum use of this tool in sustainable forest management.

Keywords: Prescribed fire; Soil productivity; Sustainable forestry

1. Introduction

Wildfire and intentional burning by Native Americans were regular occurrences in the pre-European forests of the southern United States and prescribed fire has been in continuous use since European settlement (Carroll et al., 2002). Despite this widespread use and decades of research, Christensen (1987) wrote, "The literature on fire is a bit like the holy scripture; by careful selection of results, one can "prove", for example, that fire increases, decreases, or has no effect on nutrient availability, or that fire results in considerable or negligible loss of nutrient capital from the ecosystem".

Forest fires release 1000–1750 kg CO_2, 10–250 kg CO, 10–90 kg of particulate matter, and 5–20 kg of hydrocarbons per Mg of fuel consumed (Tangren et al.,

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1976). Radke et al. (2001) state that, ''uses of planned or prescribed fires as a tool for meeting the needs of wildland managers are increasingly in collision at the air pollution control and climate change cross-roads''. Detailed guidelines have been developed to minimize the impact of prescribed burning on air quality (Pierovich et al., 1976; Riebau and Fox, 2001), but the release of CO_2 and other greenhouse gases is unavoidable. Surface fires significantly reduce carbon (C) sequestration by forests, and fire suppression in North America during the 20th century created a major C sink (Tilman et al., 2000). In some forest ecosystems, aboveground net primary productivity is inversely correlated with the frequency of surface fires (Reich et al., 2001) and periodic fires are more important than water and atmospheric deposition in regulating nitrogen (N) fluxes (Johnson et al., 1998). The many uncertainties about the long-term ecological impact of prescribed fire prompted Tiedemann et al. (2000) to question the wisdom of increased use of prescribed burning in the forest of the western USA.

The possibility that prescribed fire may adversely affect nutrient pool sizes and fluxes has been raised on several occasions (Wells, 1971; Raison, 1979; Wells et al., 1979) but has never stimulated the level of discussion and concern that occurred in the 1970s over the increasing use of mechanical harvesting and whole-tree removal (Bormann et al., 1968; Boyle et al., 1973; Kimmins, 1977; Leaf, 1979; Gessel et al., 1990). Concern that mechanical harvesting and associated practices would lower forest productivity prompted a number of long-term studies to monitor the impact of forest management practices on forest productivity (Tew et al., 1986; Hendrickson et al., 1989; Powers et al., 1990; Johnson and Todd, 1998; Briggs et al., 2000). The largest of these, the USDA Forest Service's North American Long-term Soil Productivity (LTSP) program, now consists of more than 100 LTSP and affiliated sites (Powers, 1999). However, none of these studies included an assessment of the long-term impact of forest burning on land productivity, even though prescribed fire is one of the most commonly employed management practices on both public and private land around the world.

In southern pine management, fire is used for site preparation prior to seeding or planting and during the rotation to reduce woody competition, lower the risk of wildfire, and restore or maintain certain fire-dependent ecosystems (Van Lear and Waldrop, 1991). Both site preparation and intra-rotational burns are ''prescribed fires'' in that they are intentionally ignited for the purpose of achieving a clearly defined management objective. But to avoid confusion in the ensuing discussion, the terms ''prescribed fire or prescribed burning'' will be used to mean a surface fire that burns under the canopy of an established stand of trees with minimal direct impact on the overstory. ''Site preparation or slash burning'' will refer to fires that follow logging or felling of most, if not all, of the arborescent vegetation. Fire intensity will be used to describe the upward pulse of energy which determines crown scorch or ignition. Fire severity will refer to the downward energy dispersal, which determines the consumption of the forest floor (Van Lear and Waldrop, 1989; Vose and Swank, 1993).

Prescribed fires are generally low intensity and low-severity fires conducted when fuel and soil moisture levels are moderate to high. Their fuel supply is restricted to the forest floor and understory and <50% of the available fuel is consumed in a typical burn. Prescribed burning usually begins sometime after crown closure and is repeated at varying intervals, usually 2–5 years, until rotation age. Site preparation or slash burns are conducted only once during a rotation but they are usually more severe than prescribed burns. In addition to the forest floor and understory, site preparation fires have 10 to >30 Mg ha^{-1} of logging slash and non-merchantable materials as fuel and generally consume 50–80% of available fuel.

Feller (1982) concluded that the many seemingly contradictory reports and conclusions concerning the effects of fire are due to the fact that most studies have failed to recognize or adequately quantify the various factors that influence an ecosystem's response to burning. In the ensuing report, we review the known and potential effects of fire on nutrient pools and certain soil properties and processes, the factors that cause variations in these effects, and the potential impacts of these effects on ecosystem productivity.

2. Nutrient flux from burning of forest fuels

Considerable quantities of elements are released to the atmosphere during the burning of forest fuels

Table 1
Examples of fuel consumption and elements lost during site preparation and prescribed fire in pine forests

Conditions, Locations (Reference)	Fuel consumed, Mg ha^{-1} (%)	Nutrient losses element (kg ha^{-1})
Site preparation burn following harvest of 27-year-old plantation of *Pinus radiata*, SE Australia (Flinn et al., 1979)	66.6 (84)	N (220), P (8), K (21), Ca (123)
Site preparation following a clear cut in mixed pine hardwoods, So. Appalachians USA (Van Lear and Kapeluck, 1989)	65.4 (59)	N (267)
Slash and burn regeneration of 3 separate low grade, mixed pine hardwood stands - So. Appalachians USA (Vose and Swank, 1993)	86.3 (47)	N (376.0)
	129.7 (47)	N (480.0)
	62.2 (49)	N (193.0)
Prescribed burns in natural stands of *Pinus taeda*, SE Piedmont USA (Schoch and Binkley, 1986)	2.3 (11)	N (12.0)
Three annual burns in *Pinus taeda* plantation beginning at age 40 years, SE Piedmont USA (Van Lear et al., 1990)	8.1 (n/a)	N (49)
	6.0 (n/a)	N (36)
	1.4 (n/a)	N (6)
Natural stands of *Pinus elliottii* and *Pinus palustris*, SE Coastal Plain USA (Hough, 1981)		
Not burned for 1 year	7.4 (n/a)	N (43.0), P (2.5), K (9.0), Ca (25.3), S (3.8)
Not burned for 1–2 years	6.5 (n/a)	N (39.0), P (1.5), K (9.0), Ca (12.9), S (3.4)
Not burned for 5 years	18.7 (n/a)	N (112.0), P (4.6), K (34.9), Ca (23.0), S (10.8)
Not burned for 8 years	25.4 (n/a)	N (194.0), P (8.4), K (24.5), Ca (49.5), S (17.4)

(Table 1). Elements are lost both as gases (non-particulate) and solids (particulate) borne away in the convections and wind currents created by the fire (Raison et al., 1985a). Even low-intensity prescribed burning can result in the transfer to the atmosphere of 54–75% of the N, 37–50% of the phosphorus (P), 43–66% of the potassium (K), 31–34% of the calcium (Ca), 25–49% of the magnesium (Mg), 25–43% of the manganese (Mn), and 35–54% of the boron (B) initially present in the consumed understory and litter (Raison et al., 1985b). The loss of N, K, P, and B is primarily non-particulate while that of the other nutrients is particulate. P is lost as both non-particulate, through volatilization of P_4O_{10}, and particulate wind-borne fine white ash (Raison et al., 1985a). The magnitude of nutrient losses during burning is positively and linearly correlated with fuel consumption (Hough, 1981; Raison et al., 1985a; Schoch and Binkley, 1986).

Prescribed fires usually release fewer nutrients per event than site preparation fires, although the severity of prescribed fires can vary considerably (Table 1). Wells (1971) reported that a periodic winter burn in loblolly pine (*Pinus taeda* L.) consumed 7.1 of 26.2 Mg ha^{-1} or 27% of the forest floor. In contrast, a prescribed fire in a loblolly pine stand conducted when the Oi layer was dry but the Oe and Oa layers wet, consumed just 2.3–21.3 Mg ha^{-1} or ~11% of the forest floor (Schoch and Binkley, 1986). Prescribed fires in natural stands of longleaf (*Pinus palustris* Mill.) and slash (*Pinus elliottii* Engelm.) pines consumed 6.5–7.3 Mg ha^{-1} in stands burned 1 or 2 years earlier and 18.7 and 25.4 Mg ha^{-1} in stands not burned for 5 and 8 years, respectively (Table 1). The correlation between fuel (understory and forest floor) consumed and element loss was high for C, N, P, S, and Mg, and weaker but still significant for K, Ca, and Mn (Hough, 1981).

Surface fires in southern pine stands typically consume 25–40% of the organic matter present (Brender and Cooper, 1968; Wells, 1971; Lewis, 1974) but this may be influenced by the interval between burns. Hough (1981) found that in natural mixed stands of slash and longleaf pine fuel consumption per burn was greater when the fire interval was 5–8 years than when it was 1–2 years (Table 1), but the average annual fuel consumption would be ca. 3 Mg ha^{-1} per year with a 5–8 years cycle compared with 6–7 Mg ha^{-1} per year with an annual or biennial cycle (Table 1). Litterfall in southern pine stands averages 5–7 Mg ha^{-1} per year (Jorgensen et al., 1980; Lockaby and Taylor-Boyd, 1986; Ross et al., 1995) and litter may become less combustible as it decomposes.

Wells (1971) estimated that the winter burn that consumed 7.1 Mg ha^{-1} of fuel released 109 kg ha^{-1} of N or 15.4 kg N Mg^{-1} of fuel consumed, but this seems too high. Both Hough (1981) and Schoch and Binkley (1986) working with different pine species and widely different fire severities reported values of 5–6 kg N Mg^{-1} of fuel consumed. Flinn et al. (1979) estimated the N loss at 3–4 kg Mg^{-1} during burning of pine logging slash.

The loss of P during fires in southern forests may be as significant as the loss of N since many southern pine sites are P deficient (Jokela et al., 1991). Up to 50% of the P in surface materials may be released to the atmosphere during burning with 28–88% of this P as non-particulate (gaseous) form representing a potential loss from the ecosystem (Raison et al., 1985b). The particulate fraction of P, a fine ash in which P can be concentrated 50-fold, returns to earth rather quickly, resulting in redistribution within rather than a loss from the stand or ecosystem (Cook, 1994). However, certain sites and aspects tend to burn more frequently than others which could lead to P impoverishment of the burned sites (Handreck, 1997). Potassium also is gasified during burning but K is rapidly leached from litter to the soil which may explain why repeated burning did not lower soil K levels (Wells, 1971).

3. Nutrient inputs by natural processes

Forest ecosystems receive regular nutrient inputs by atmospheric deposition and mineral weathering, however, soils of the southern Coastal Plain are highly weathered and annual inputs of nutrients from further weathering are probably negligible (Jorgensen and Wells, 1986). Jorgensen and Wells (1986) state, "Precipitation contributes significant amounts of nutrients for growth and maintenance of loblolly pine", and estimate the average annual inputs per hectare for the natural range of loblolly pine at 5.9 kg N, 0.4 kg P, 1.7 kg K, 1.7 kg Mg, and 7.2 kg Ca. These figures are too high for precipitation or wet deposition alone but may be a reasonable estimate of total (wet + dry) input. Across the southern pine region average annual inputs by precipitation range from 2.8–3.9 kg N ha^{-1}, 0.63–1.11 kg K ha^{-1}, 0.02–0.37 kg Mg ha^{-1}, and 0.56–2.08 kg Ca ha^{-1} (Anonymous, 2002; Lavery et al., 2002). For many nutrients, however, the majority of atmospheric deposition occurs in dry deposition of soil (fugitive dust) and other fine particulates. On a forested watershed in Tennessee, 60–70% of the total annual atmospheric deposition of Ca (8.4 kg ha^{-1}) and K (0.4 kg ha^{-1}) resulted from dry deposition (Lindberg et al., 1986). The average annual input of P by precipitation in Florida was ~0.013 kg ha^{-1} and did not differ significantly among 13 recording stations, but total deposition exceeded 0.41 kg ha^{-1} at some sites (Ahn and James, 2001; Grimshaw and Dolske, 2002). In the southern Coastal Plain, dry deposition represents about one-third of the total N deposition (Lavery et al., 2002). However, like the inputs of nutrients from the ash of forest fires, the inputs of nutrients attached to soil particles may be redistribution rather than net gain.

N is added to terrestrial ecosystems by the fixation of N_2 by free-living and/or symbiotic organisms. Estimates of total biological N fixation in southern pine ecosystems, from both nodulated higher plants and free-living soil organisms, range from <0.3 to >7 kg ha^{-1} per year (Van Lear et al., 1990; Boring et al., 1991; Hendricks and Boring, 1999).

It has been hypothesized that burning increases N_2 fixation by legumes, which compensates for the N losses due to burning (Wells, 1971; Waldrop et al., 1987; Van Lear et al., 1990; Boring et al., 1991). However, the biomass of nodulated plants in well-stocked southern pine stands is usually insufficient to fix quantities of N comparable to that reported for species such as *Ceanothus* sp. on burned sites in the western US (Wells et al., 1979). Hendricks and Boring (1999) measured symbiotic N_2 fixation in four stands of loblolly pine regeneration 2–3 years after clear cutting and burning. Two of the stands had been burned at 4–5 years intervals for 30 years during the previous rotation. The other two stands had not been burned during the previous rotation. On the frequently burned sites, dense population of legumes added 7–9 kg N ha^{-1} per year to the ecosystem. The authors concluded, ''... nitrogen inputs via N_2 fixation by enhanced legume populations may balance the nitrogen losses due to burning'', but this would require that fuel consumption by burning not exceed 1–2 Mg ha^{-1} per year and legume density not diminish as the pine overstory develops. Neither of these conditions appears likely. Replacing the N loss during the site preparation burn would take ~20 years if N_2 fixation remained at 9 kg ha^{-1} per year and no further burning occurred. The open, lightly stocked pine stands and savannahs that existed when European settlers first arrived in the Southern Coastal Plain may have supported extensive stands of leguminous plants (Hainds et al., 1999) but Haywood and Harris (1999) found herbaceous growth was low and predominately grasses in well-stocked (basal area 19–26 m^2 ha^{-1}) longleaf pine stands even when burned at 2–3 years interval.

Coarse woody debris such as logging slash and stumps is reported to provide active sites of N fixation during the process of decomposition (Jurgensen et al., 1997; Wei and Kimmins, 1998) but the importance of such N inputs in southern forests has not been evaluated. Barber and Van Lear (1984) reported that the N content of loblolly pine logging slash first declined and then increased to 107% of the initial content 7 years after logging; however, the increased N probably came from atmospheric deposition or throughfall (Jorgensen and Wells, 1986). Site preparation burning and prescribed fire would reduce coarse woody debris and, hence, the potential for N input from this source.

Van Lear et al. (2000) found that the N concentration in loblolly pine stumps and large roots after 16 years of decomposition was >40 times higher than the N concentration in adjacent mineral soil and the biomass of 16-year-old loblolly pine trees within 1 m of a decaying stump was 97% greater than that of trees >3 m from a decaying stump. Wei and Kimmins (1998) measured N fixation rates in coarse woody debris in harvested or burned lodgepole pine (*Pinus contorta* Dougl.) stands on dry, infertile sites in north-central British Columbia. They found that N fixation was sensitive to moisture and temperature variation with the highest rates occurring in below-ground debris, i.e., stumps and large roots. Using the mean rate of N fixation reported by Wei and Kimmins (1998) and the estimated stump and root biomass (22.5 Mg ha^{-1}) for a 27-year-old loblolly pine stand (Carter et al., 2002), N fixation in stumps and roots could be ~19 g ha^{-1} per day, or, assuming 180 days of suitable temperature and moisture, 3–4 kg ha^{-1} per year.

There have been occasional reports of high rates of N accretion from non-symbiotic sources (for example, see Bormann et al., 1993). However, in a recent review, Binkley et al. (2000) concluded that there is no creditable evidence for non-symbiotic inputs of N exceeding ~10 kg ha^{-1} per year. Richter et al. (2000), in a carefully conducted study, found that in the absence of fire, a loblolly pine ecosystem in South Carolina gained 204.7 kg ha^{-1} of N during a period of 35 years for an accretion rate of 5.9 kg ha^{-1} per year, which they noted was similar to the rate of atmospheric N deposition.

Historically, fire, both spontaneous and human induced, has been an important ecological process in southern pine forests (Carroll et al., 2002). Olson (1981 as quoted in Hainds et al., 1999) estimated that fires in pre-European longleaf pine landscapes resulted in an average loss of 100 g C m^{-2} per year or 2 Mg biomass ha^{-1} per year, which would mean losses of ~12 kg N ha^{-1}, 0.54 kg P ha^{-1}, 1.9 kg K ha^{-1}, 3.8 kg Ca ha^{-1}, and 0.82 kg Mg ha^{-1} per year, approximately equal to the inputs for these elements, assuming biological fixation of N_2 was in the range of 7–9 kg ha^{-1} per year, as suggested by Hendricks and Boring (1999), and atmospheric deposition was similar to what it is today. The fact that southern pine forests have prevailed for several thousand years suggests that frequent surface fires do not threaten the continued existence of these forests. But these pre-European forests were not subjected to additional nutrient losses due to harvesting and site preparation burning.

4. Inputs versus losses

An estimate of the potential losses and gains of nutrients over a 25-year rotation of loblolly pine managed with prescribed burning is presented in Table 2. Whole-tree harvesting would remove twice as much N and 1.5 times as much P and K as bole-only

Table 2
Estimated flux of major nutrients in a loblolly pine plantation over a 25-year rotation under a system of whole-tree harvesting without fire versus boles-only harvesting with site preparation burning and prescribed fire

Source of nutrient flux	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	Ca (kg ha^{-1})	Mg (kg ha^{-1})
Nutrient losses: whole-tree harvesting and exclusion of fire during rotation[a]	137	11	79	140	41
Inputs from natural processes[b]	173	10	43	180	43
Net change over rotation	+36	−1	−36	+40	+2
Nutrient losses: bole-only harvesting[a]	59	5	48	111	29
Nutrient losses: site prep fire[c]	280	5	26	99	11
Nutrient losses: intra-rotation fires[c]	108	4.9	17.5	34.9	7.4
Inputs from natural processes[b]	273	10	43	180	43
Net change over rotation	−175	−4.9	−48.5	−64.9	−4.4
Soil supply (0–60 cm)[d]	1424	5	85	832	145

[a] Based on a 25-year rotation and a mean annual increment of ~10 m^3 ha^{-1} per year (data from Carter et al. (2002)).
[b] Nutrient depositions based on Jorgensen and Wells (1986). N_2 fixation estimated at 1 kg ha^{-1} per year w/o fire; 5 kg ha^{-1} per year w/o fire.
[c] Assumes 84% of organic residues consumed in site prep burn (Flinn et al., 1979). Prescribed burns at ages 12, 17, and 22 years with average fuel consumption of 6 Mg ha^{-1} per burn (Hough, 1981).
[d] Kirbyville series, southeast Texas (Carter et al., 2002).

harvesting but bole-only harvesting followed by a site preparation burn would remove as much P, K, and Mg and more N and Ca than whole-tree harvesting without burning even after allowing for increased N_2 fixation as a result of burning. Some nutrients would leach from the logging slash during the interval between logging and burning. During the first 12 months after harvesting, woody loblolly pine logging slash loses only 7–10% of all major elements (Barber and Van Lear, 1984), but needles lose of 70% K, 50% P, 50% Mg, 25% Ca, and <10% of N (Jorgensen et al., 1980). However, it is not known how long nutrients leached from logging slash remain in the combustible materials on the forest floor before moving to the non-combustible mineral soil. When the losses by prescribed fires are added to those resulting from harvesting and site preparation, the result is a net loss of all the major nutrients (Table 2). Lengthening the rotation would reduce nutrient loss per ton of harvested wood (Switzer et al., 1966), but would also increase the number of prescribed burns.

Not all of the elements gasified during burning of surface fuels are lost from the site. The following section cites several reports of increased soil available nutrients following surface fires. The origin of these increases is not firmly established but it is probable that a portion at least of the N gasified during combustion of surface fuels enters the soil. The same may be said of P, S and K, which also are gasified during burning (Raison et al., 1985a).

5. Effects of fire on soil

5.1. Soil physical properties

In the US Southern Coastal Plain erosion and leaching losses due to prescribed fire are usually negligible (Jorgensen and Wells, 1986; Van Lear and Waldrop, 1989). Site preparation or slash burns pose a greater risk of soil erosion than prescribed fires (Wells et al., 1979; Van Lear and Kapeluck, 1989; Robichaud and Waldrop, 1994). Van Lear and Danielovich (1987) and Farrish et al. (1993) reported that soil losses from harvested and burned sites in South Carolina and Louisiana, respectively, were low when burns were conducted under prescribed conditions. However, soil losses were significantly higher following high-severity site preparation burns (Robichaud and Waldrop, 1994) or when burning was followed by mechanical site preparation (Farrish et al., 1993).

Vitousek and Matson (1985) reported significant leaching of NO_3^- following harvesting and site preparation in coastal North Carolina, but in their studies, site preparation burning was combined with mechanical treatment. Knoepp and Swank (1993) reported little change in the movement of inorganic N in soil water or stream flow during the 12 months following slash and burn site preparation in western North Carolina.

Removal of surface cover leaves soils susceptible to the kinetic effects of raindrops, which can disperse soil aggregates and clog soil pores (Ralston and Hatchell, 1971; Wells et al., 1979). Repeated burning over a period of several years can lead to increased bulk density and reduced macropore space, infiltration rates, and moisture holding capacity (Ralston and Hatchell, 1971; Boyer and Miller, 1994). A single site preparation or slash fire is not likely to affect soil compaction (Oswald et al., 1999; Giardina et al., 2000a) although surface crusting may result with some soils (Harrington et al., 1998). Wildfire and slash burning often result in the formation of a water-repellent layer near the soil surface, which reduces water infiltration and increases the risk of erosion (DeBano, 2000; Robichaud, 2000).

Heating of soil to temperatures above 100 °C can alter the cation exchange and moisture holding capacities of soil colloids due to the oxidation of soil organic matter and loss of adsorbed water by clay micelles (Ralston and Hatchell, 1971). Soil temperatures rarely reach 100 °C during prescribed fires but may reach or exceed this level to a depth of several centimeters during slash burning or stand-replacing wildfires (Dyrness and Youngberg, 1957; Ralston and Hatchell, 1971; Flinn et al., 1979; Oswald et al., 1999; Giardina et al., 2000a).

5.2. Soil nutrients

Burning of surface fuels results in a concentration of metallic cations, e.g. K, Ca, Mg, in the ash and unburned residues (Wells et al., 1979). Wells (1971) reported that 20 years of annual winter fires had no effect on soil K levels but significantly increased Ca and Mg in the surface 5 cm of mineral soil and increased pH ~0.5 unit in both the forest floor and surface 5 cm of mineral soil. Most of the increase occurred in the first 10 years. Waldrop et al. (1987) concluded that burning resulted in a transfer of Ca from the forest floor, where it was not available to plant roots, to the mineral soil where it became available. Binkley et al. (1992) also found that periodic burning increased exchangeable Ca in the surface soil, but found no differences in K or Mg levels and no clear pattern of change in soil pH related to burning. This latter finding contrasted with an earlier report from a better drained portion of the same study area (Binkley, 1986), suggesting that soil drainage or moisture content exerts an influence on the effects of fire on soil processes (Binkley et al., 1992).

The effect of forest fires on N availability has been of particular interest to investigators since N availability is one of the most common limiting factors to forest productivity worldwide (Fisher and Binkley, 2000). After a meta-analysis of data from 87 studies, Wan and Luo (2001) concluded that the only consistently significant effect of fire on soil N was an increase in the concentration of mineral N (NH_4^+ and NO_3^-) in the surface soil immediately after burning. Fuel N concentration, soil total N concentration and soil total N amount were not significantly changed by fire. However, the majority of the data included in the meta-analysis came from short-term studies, and the effects of fire on N dynamics vary among ecosystems and with time following burning (Johnson and Curtis, 2001).

Covington and Sackett (1986) and Ryan and Covington (1986) found that soil mineral N increased 70–100 kg ha^{-1} following prescribed burning in ponderosa pine (*Pinus ponderosa* Dougl.) stands and concluded that periodic burning could be used to increase N availability. Schoch and Binkley (1986) reported that a light surface fire in a 50–60-year-old stand of loblolly pine resulted in the release of 60 kg N ha^{-1} more than was measured in an unburned portion of the stand. Monleon et al. (1997) also found increased levels of soil mineral N 4 months after burning in ponderosa pine stands but these differences disappeared after 12 months.

Covington et al. (1991) concluded burning resulted in a large increase in soil NH_4^+ which stimulated development of nitrifying bacteria leading to a decline in NH_4^+ and an increase in NO_3^-. Nitrate levels eventually return to pre-burn levels as a result of plant uptake, leaching, and/or microbial immobilization. Other investigators have reported similar changes in mineral N following burning (see review by Wan and Luo (2001)). But increased levels of NO_3^- are not always detected following burning. In the southern Appalachians Mountains, slash burning increased soil NH_4^+ levels for up to 12 months but no increase in

NO_3^- was found (Knoepp and Swank, 1993). Nitrification is frequently masked by high rates of microbial consumption/immobilization of NO_3^-, especially when moisture and SOM are high (Stark and Hart, 1997), which could explain why Knoepp and Swank (1993) did not detect higher levels of NO_3^- after burning.

The origin of the higher levels of NH_4^+ in the soil after burning is unclear. Grogan et al. (2000) concluded that surface ash was a major source of the increases in soil mineral N. Using a leaf-blower, they removed the surface ash from a series of plots following a severe wildfire in *Pinus muricata* D. Don. After one growing season, biomass and biomass N were three times greater on plots with ash than on plots where ash was removed. There was no difference in soil mineral N, but total N in the upper 10 cm of soil was 20% higher where the ash was not removed. Giardina et al. (2000a,b) argue that ash is not an important source of increased soil available nutrients following burning. In one study (Giardina et al., 2000a), 74% of N in the surface ash was lost from the site in wind currents during the 28 days between burning and the first rain, but organic N in the surface soil deceased 150 kg ha^{-1} while KCl-extractable N increased by 82 kg ha^{-1} immediately after burning. Similar changes were observed for P. The authors concluded that soil heating during slash fires converts nutrients from non-available to available forms. Another possible source of increased soil mineral N following burning was proposed by Knoepp and Swank (1993). They suggested burning results in the downward movement of NH_3, which condenses in the lower, cooler soil layers.

A number of investigators have reported increased rates of N mineralization in the forest floor and/or the surface soil following burning (Schoch and Binkley, 1986; White, 1986; Fyles et al., 1991; Knoepp and Swank, 1993; Prieto-Fernandez et al., 1993; Connell et al., 1995; Weston and Attiwill, 1996). Elevated N mineralization rates may persist for 12 months or more but after longer periods or after repeated burning, the rate of N mineralization on burned sites is generally below that of unburned sites. For example, Monleon et al. (1997), working in ponderosa pine stands in Oregon, found increased N mineralization in the soil 6 months after prescribed burning but not after 12 months. Stands burned 5 years earlier had lower mineral N and lower N mineralization rates than unburned stands. Other investigators have reported similar findings (Hossain et al., 1995; Dumontet et al., 1996; Wright and Hart, 1997; DeLuca and Zouhar, 2000; Ellingson et al., 2000; Choromanska and DeLuca, 2001; Reich et al., 2001). Monleon et al. (1997) concluded that the long-term effect of periodic fires was to reduce the availability of soil N. Wright and Hart (1997) reached a similar conclusion after finding that 20 years of biennial burning [on the same ponderosa pine sites used by Covington and Sackett (1986) and Ryan and Covington (1986)] resulted in the loss of 110 kg ha^{-1} of total N from the upper 15 cm of soil and 470 kg ha^{-1} from the forest floor.

Studies of the effects of burning on soil N in the southern pine stands have produced conflicting results. Wells (1971) found that 30 years of repeated prescribed fire in a loblolly-longleaf pine stand reduced the amount of N in the forest floor but increased N in the mineral soil for no net change. Waldrop et al. (1987) reported that total N in the forest floor was reduced but was unchanged or only slightly higher in the surface 10 cm of mineral soil after 30 years of annual burning in a loblolly pine stand. Binkley et al. (1992) measured soil N in the same area studied by Waldrop et al. (1987) and concluded that 30 years of annual burning resulted in a loss of 300 kg N ha^{-1} from the floor and surface 20 cm of soil (Fisher and Binkley, 2000). Neither Waldrop et al. (1987) nor Binkley et al. (1992) evaluated differences in the N content of the non-pine biomass which was considerably greater on the unburned plots (Waldrop et al., 1987); inclusion of this biomass N would increase the estimate of N loss from repeated fires by 20–50 kg ha^{-1}.

Several investigators (Wells, 1971; McKee, 1982; Waldrop et al., 1987) have reported that burning increased available soil P in loblolly and longleaf pine stands while others detected no change (Binkley et al., 1992; Boyer and Miller, 1994; Ross et al., 1995; Haywood et al., 1995). Such discrepancies may be due to difference in fire severity, different ambient levels of P in the soils, different time intervals between burning and soil sampling, and/or different measures of P availability.

McKee (1982) states, "Prescribed burning consistently increased the amount of available P" but the increase was not significant at all sites. McKee (1982) termed dilute acid fluoride (Bray #2) extracts, ''available'' P, and 1.0 N NH_4Cl extracts, ''water soluble'' P. At two sites, where ambient levels of P were 36 and 70 meq kg^{-1}, annual winter burning increased ''available P'' 48–50%. But burning had no effect at a site where ''available'' P concentration was 23 meq kg^{-1}. Likewise, annual winter burning increased ''water soluble'' P 30% at a site where ambient levels were 10.7 ppm but had no effect at two other sites where ambient levels were 4.4 ppm or less. McKee (1982) assumed that the increase in available P resulted from combustion of the forest floor materials and subsequent incorporation of P containing ash into the surface mineral soil, although he acknowledged that the increases in soil P were quite small compared to the reduction in P in the forest floor after burning.

Plants absorb P only as inorganic ions (P_i) from the soil solution (Holford, 1997). In soil, P_i exists in a dynamic equilibrium with a complex mixture of nonionic inorganic and organic forms and no single component can be clearly identified as ''plant-available'' P (Holford, 1997). However, a fractionation procedure developed by Hedley et al. (1982) is often used to quantify various forms of soil P and estimate P availability (Cross and Schlesinger, 1995). In this process, soil is first extracted with anion exchange resin in deionized water, which removes dissolved P_i. Next the soil sample is extracted with 0.5 M $NaHCO_3$, which removes P_i and easily mineralized organic P (P_o) lightly bound to the surface of soil colloids. Together these two fractions are believed to estimate ''plant-available'' P. Several additional steps extract various forms of P_i and P_o which are not available to plants although some may become available over long periods (Cross and Schlesinger, 1995).

Using the Hedley procedure, Saa et al. (1994) investigated the effects of fire on soil P in the Mediterranean region of Spain. They found that a moderate forest fire resulted in little or no change in plant-available P in the soil but a severe fire caused >50% increase in both the available and non-available P_i with a corresponding decrease in the P_o of both fractions. Giardina et al. (2000a), also using the Hedley procedure, reported that the quantity of non-plant-available (both P_i and P_o) that was thermally transformed into plant-available forms (35 kg P ha^{-1}) exceeded the total quantity of P contained in pre-burn slash (27 kg P ha^{-1}), of which <25% was transferred belowground. Both Saa et al. (1994) and Giardina et al. (2000a) findings were based on soil samples collected a few days after burning. Ten months after burning, Saa et al. (1994) found no differences in soil P between the severe burn and the moderate burn.

In laboratory studies, DeBano and Klopatek (1988) found that burning wet soil resulted in no change in soil P, but burning dry soil produced a significant increase in bicarbonate extractable P_i which disappeared 45 days after burning. Chambers and Attiwill (1994) working with soil from a *Eucalyptus* regnans forest found that potentially available N was increased by heating the soil to 100 °C but significant increases in P availability were not detected until soil temperature reached 400 °C. Temperatures above 100 °C are not reached until all soil moisture has evaporated, thus soil moisture, along with fire severity and duration determine the depth and level of soil heating and the amount of change in soil N and P availability (DeBano, 1990).

It is unlikely that prescribed burning causes chemical changes in N or P forms in the soil since temperatures usually do not exceed 50–60 °C in the upper 10 cm of soil during surface fires (Saa et al., 1993; Preisler et al., 2000). However, slash fires may produce much higher soil temperatures. Giardina et al. (2000a) recorded soil temperatures >500 °C in the surface 0.5 cm, 200 °C at 2 cm and 100 °C at 3 cm during a slash fire on a dry soil. Dry soil is a poor thermal conductor and temperature curves in the soil under a surface fire are quite steep (DeBano, 2000). Wan and Luo (2001) concluded that the surface soil must be sampled in thin layers to adequately assess the ecologically significant changes in soil nutrients that result from burning.

In most highly acid mineral soils, P_i availability is greatly reduced by the formation of insoluble hydroxy phosphates (Brady, 1990). This process is increased by soil heating and decreased by raising soil pH (Fisher and Binkley, 2000). Oswald et al. (1999) and Giardina et al. (2000a) reported large increases in available P following slash burning on inceptisol or entisol with pH 6.6–7.0, near optimum for P availability. Increases in available P following burning on more acid soils have been smaller and usually accompanied by small but significant increase in soil pH (McKee, 1982; Simard et al., 2001).

Prescribed burning may result in small increases in soil available P as the result of gaseous movement during burning and leaching or microbial transfer from surface ash. However, the large increases that sometimes follow severe fires most likely result from heat induced conversion of non-available P in the soil to available forms.

6. Effects of fire on forest productivity

6.1. Fire and N availability

Richter et al. (2000) found that in 40 years an old-field loblolly pine plantation, not burned since establishment, accumulated such large quantities of nutrients in standing biomass and forest floor that it was in an acute state of nutrient deficiency despite substantial inputs and a history of agricultural fertilization. Several authors have made similar observations about pine-dominated ecosystems and inferred that prescribed burning could promote pine productivity (Covington and Sackett, 1986; Schoch and Binkley, 1986; Peterson et al., 1994; Covington et al., 1997; Feeney et al., 1998). Although this expectation seems logical, there is no definitive evidence that prescribed burning increases pine productivity. Peterson et al. (1994) reported that a fire interval of 4–6 years provided adequate fuel reduction in ponderosa pine stands, but growth remained unaffected. Other authors have reported that repeated burning reduced growth of ponderosa pine (Landsberg et al., 1984; Cochran and Hopkins, 1991; Busse et al., 2000). Feeney et al. (1998) found that fire increased oleoresin flow and suggested that the use of prescribed fire could increase the resistance of ponderosa pine to bark beetle attack. Santoro et al. (2001) recorded increased resin flow in *Pinus resinosa* Ait. following burning, but also observed increased insect populations and incidences of insect attack. They concluded that overall, surface fires probably increased the demographic impact of bark beetles.

Waldrop et al. (1987) expressed surprise that 30 years of annual burning had no significant effect on the growth of loblolly pine, since, ‘‘We expected that the control of competing vegetation and increased soil fertility resulting from prescribed burning would improve growth rates (for pine)’’. Their expectation for ‘‘increased soil fertility’’ was based on Wells (1971) and McKee (1982). They did not discuss the fact that unburned plots had slightly more pine and considerably more non-pine basal area than burned plots, which suggests that total biomass production was notably less on the burned plots. Instead they concluded that the overstory pines, which averaged 40-year-old at the start of the studies, ‘‘were probably too old to respond ...’’.

In longleaf pine, 18 years of biennial burning beginning at age 14 resulted in a 27% decrease in volume growth (Boyer, 1993). Supplemental treatments to control understory competition did not increase pine growth. There were no differences due to season of burning—winter, spring, summer—although crown scorch was 16% for summer burns compared to 9% for winter. In a later report from the same study, Boyer and Miller (1994) found no differences in nutrient concentrations in the surface soil or pine needles due to burning. However, they found small but significant differences in soil bulk density (1.22 kg l^{-1} for unburned versus 1.26 kg l^{-1} for winter burn) and macropore space (47.1% for unburned versus 44.5% for winter burn). They suggested that biennial burning could have reduced pine growth by altering soil–tree moisture relations, although they found it, ‘‘... difficult to believe that the relatively small changes in soil moisture holding capacity’’ could be responsible for a reduction in growth rate of 2.2 m^3 ha^{-1} per year (20%). Zahner (1989) found that winter burning reduced radial growth of longleaf pine an average of 13% during the year following burning. The growth reduction was increased to 27% by drought and negated by high moisture supply. But Boyer (1993) found that reducing understory competition, thus improving moisture supply for the pines, failed to improve pine growth, which adds to the skepticism that reduced pine growth on the burned plots was due solely to greater moisture stress.

Ecosystem productivity (annual aboveground net primary productivity, ANPP) is highly correlated with N availability (as determined by the rate of N mineralization or litterfall N) in a broad spectrum of forest ecosystems, ranging from unmanaged natural stands of broadleaf species to intensively managed plantations of conifers (Reich et al., 1997; Carlyle and Nambiar, 2001). Recently, Reich et al. (2001), using data from 20 mature oak savannas, reported that ANPP, while directly related to N mineralization ($r^2 = 0.79$), was inversely correlated with fire frequency ($r^2 = 0.59$). Conversely, ANPP was inversely related to soil N mineralization on frequently burned longleaf pine-wiregrass sites, which varied from excessively drained to poorly drained (Mitchell et al., 1999; Wilson et al., 1999, 2002). However, litterfall N, another measure of ecosystem N supply (Reich et al., 2001) was directly related to ANPP. All sites were burned shortly before monitoring of N mineralization began but no information on fire severity was reported. Apparently, fire-induced changes in soil and litter N mineralization altered, at least temporarily, the usual relationship between the N mineralization rate and ANPP.

The rate of N mineralization in the forest floor is correlated with total (litter plus soil) N mineralization and dependent upon litter quality[1] (Stump and Binkley, 1993; Carlyle and Nambiar, 2001). Monleon et al. (1997) suggested that frequent surface fires reduce the substrate quality, i.e. increase the C/N ratio, which results in lower rates of N mineralization and reduced forest growth. Periodic burning generally reduces both litter quantity and quality. Unburned stands of loblolly pine, over 15-year-old, typically have 30–40 Mg ha^{-1} biomass in the forest floor with N concentrations of 10–12 kg Mg^{-1} whereas stands burned periodically have less biomass and lower N concentrations (Tew et al., 1986; Schoch and Binkley, 1986; Binkley et al., 1992; Carter et al., 2002). For example, Binkley et al. (1992) reported that after 30 years, unburned plots of loblolly and longleaf pine had 38 Mg ha^{-1} of biomass in the forest floor with a $C/N = 37$; plots burned every 4 years had 25 Mg ha^{-1} and $C/N = 46$; plots burned every 2 years had 18 Mg ha^{-1} with $C/N = 55$; plots burned annually had 6 Mg ha^{-1} and $C/N = 56$. Less biomass and higher C/N ratios in the forest floor of stands subjected to prescribed burning is an indication that N mineralization and ecosystem N supplies are less than they would be in the absence of prescribed fire.

6.2. Fire effects on species composition and competition

Miller and Bigley (1990) found that slash burning altered species composition and the distribution of growth but not total productivity. They analyzed the growth on 44 pairs of burned and unburned plots in Oregon and Washington 35–42 years after burning and found no differences in Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) site index or in mean annual increment in total volume. However, volume growth of Douglas-fir and hardwood was greater and other conifers correspondingly less on burned plots than on unburned plots.

Squire et al. (1985) concluded that nutrient losses during slash burning (Flinn et al., 1979) were the cause of reduced productivity in second rotation *Pinus radiata* D. Don. plantations in southeast Australia. Subsequent studies determined that productivity declines due to nutrient losses were restricted to highly infertile sites (Smith et al., 2000). On better sites, burning logging slash resulted in increased growth of herbaceous weeds which, if not controlled, reduced pine growth and yield (Nambiar, 1990).

Neary et al. (1999) states that low-severity fires increase plant-available nutrients and promote herbaceous growth while high severity fires cause mortality of seed and root systems in the surface soil leading to reduced herbaceous growth. But Jensen et al. (2001) found that increasing fire severity favored grasses over broad-leaf herbs while Grogan et al. (2000) concluded species that rapidly produce root or stump sprouts benefit the most from severe fires.

Most long-term site preparation studies in the southern USA have confounded burning with mechanical treatment making it impossible to evaluate the specific effect of burning (Vitousek and Matson, 1985; Haywood and Burton, 1990; Anonymous, 1991; Edwards, 1994; Miller et al., 1995; Tiarks and Haywood, 1996). Since the introduction of imazapyr-type herbicides (Shaner and O'Connor, 1991), aerial application of chemicals has replaced mechanical treatment for control of woody competition in pine plantations. But broadcast burning 2–4 months after aerial spraying, so called ‘‘brown and burn’’, is still used to reduce the large amounts of logging slash and facilitate planting and other cultural treatments. Minogue and Lauer (1992) found no difference in pine growth between burn and no burn treatments following application of 2.2 kg ha^{-1} (a.i.) imazapyr. However, 2.2 kg ha^{-1} is 2–4 times recommended rates for site preparation in loblolly pine (Beardmore et al., 1991). Harrington et al. (1998) found that burning after application of

[1] Expressed as C/N ratio although lignin/N ratio is probably more appropriate (Stump and Binkley, 1993).

imazapyr alone, at 0.56 or 0.84 kg ha^{-1}, increased loblolly pine growth while burning after application of imazapyr mixed with glyphosate, triclopyr, or picloram, resulted in greater herbaceous competition, especially from grasses, and reduced pine growth. Harrington et al. (1998) did not indicate whether fuel loading or fire severity differed between sites treated with imazapyr alone and sites treated with a mixture of chemicals. If the mixture of chemicals resulted in a more extensive ‘‘brown-out’’ and a more severe fire, the greater removal of surface cover and larger increase in mineral N could have stimulated increased herbaceous competition, especially from grasses. Shiver and Martin (2002) found that ‘‘brown and burn’’ followed by 3 years of control of all competition resulted in significantly greater growth of planted pines than burning or ‘‘brown and burn’’ without subsequent competition control.

In a study in Brazil (Stape et al., 2001; Fisher and Binkley, 2000), clones of *Eucalyptus grandis* × *urophylla* were planted on a high and a low quality site with and without burning prior to planting. All competing vegetation was controlled by repeated application of herbicide. After 3 years, burned plots on the high site had significantly higher LAI and ~15% greater biomass. On the low productivity site, burned plots had greater LAI and >100% greater biomass. Increased P availability was a likely result of the burning, since the foliar P levels in the burned plots were nearly twice those for unburned plots. However, the two-fold increase in LAI suggests that more N was available as well. By the 5th growing season, there were no differences in LAI or current annual increment between burned and unburned plots (Stape, 2002, personal communication), indicating that the effect of burning was transitory. Over the 6 years rotation used for *Eucalyptus* production in Brazil, site preparation burning had a profound effect on plantation yield at rotation. With crop species that grow more slowly—the eucalypts were 12–15 m tall at age 36 months—competing herbaceous species and woody stump and root sprouts may be the principal beneficiaries of the transitory increase in soil N and P availability following severe site preparation burns.

Elliott et al. (2002) reported that, after eight growing seasons, height, diameter, and volume of white pine (*Pinus strobus* L.) planted following slash and burn site preparation, were inversely correlated with the amount of forest floor (Oi layer) consumed by the burning. The authors concluded, quite logically, that, ‘‘The loss of site N capital (in the Oi layer) could have a significant negative effect on growth of planted white pine over the long term’’. However, on the same sites used by Elliott et al. (2002), Knoepp and Swank (1993) reported that the increase in soil NH_4^+ and N mineralization following burning appeared to be directly related to fire severity. This, in turn, may have resulted in increased competition for the planted pine on the more severely burned areas. But reduced N pools and lower ANPP may be the more significant long-term effect of burning.

7. Summary and conclusions

The nutrients lost during natural surface fires or prescribed burning may be replaced by natural inputs during the ensuing rotation but a corollary to this conclusion is that burning prevents or reduces an increase in nutrient capital that would occur in the absence of fire. Short-term increases in soil-available nutrients that result from prescribed fires are captured by understory vegetation and these benefits appear to be more than offset by a long-term reduction in the nutrient capital, especially N. In pre-European North American forests, the rate at which nutrients were lost due to periodic wildfire probably was at or near equilibrium with the rate of inputs through natural processes. But wildfire was a major factor controlling ANPP in these forests.

Fire may lower the overall productivity (ANPP) of a forest ecosystem without reducing timber production or reduce timber production without reducing ANPP. Repeated annual or biennial burning can all but eliminate understory hardwood species without reducing pine yield (Waldrop et al., 1987) although ANPP almost certainly is reduced by the elimination of the understory component. Broadcast burning following harvesting may increase ANPP but pine regeneration growth and yield maybe be reduced unless competing vegetation is controlled. When forest management practices include a combination of timber harvesting, broadcast burning of logging slash, and frequent prescribed burns during the timber rotation, there is a high likelihood that nutrient losses will result in a reduction in both ANPP and timber yields unless those losses are mitigated by fertilization and/or competition control.

Prescribed fire has a number of beneficial effects which may offset any losses in productivity or justify the cost of mitigating practices such as fertilization and competition control. However, optimizing the benefits of prescribed fire will require an extensive understanding of the near- and long-term effects of burning on soil and ecosystem processes, as well as the closely controlled application of this management tool.

The objective of this report is not to suggest that the use of prescribed fire be eliminated or even reduced in forest management. Nor do we wish to imply that productivity, either ANPP or timber yields, should be the ultimate goal of management. Rather we wish to emphasize to forest mangers that the impact of fire on factors affecting productivity and yield and raise questions about the long-term effects of prescribed burning in combination with other management practices such as whole-tree harvesting and broadcast burning for site preparation that remove large quantities of essential nutrients from the ecosystem. In doing so, we hope to stimulate further research on the effects of fire on soil and ecosystem processes especially as they relate to sustainable forest management.

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